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Electricity generation from renewables in the United States: Resource potential, current usage, technical status, challenges, strategies, policies, and future directions

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ABSTRACT

In order to secure the energy future and protect the environment, the U.S. is looking for renewable resources to meet the increasing energy demands for its electricity sector (which accounts for ≈ 40% of total U.S. energy consumption in 2011). The overall aim of this article is to summarize the possible approaches that can be used to improve and optimize the utilization of renewables for electricity generation in the United States. First, an overview is presented about the resource potential, current usage, and technical status of electricity generation from renewables (in the United States). Second, a number of economic, operational, regulatory, sustainability, and technical challenges that are likely to be encountered are identified. Third, strategies are outlined that can be used to minimize costs, deal with the spatial nature of renewables, smooth temporal variations associated with intermittency, and achieve successful integration of electricity generated from renewable resources into the U.S. power grid. Fourth, a sustainability assessment framework for renewable resource deployment (for electricity generation in the U.S.) is discussed. The framework considers multiple criteria (including cost, environmental and social impacts), thus giving a comprehensive assessment of each renewable energy resource (for electricity generation in the United States). Fifth, the current U.S. renewable energy policy is analyzed, and rigorous recommendations are made for optimizing future U.S. renewable energy policy that can permanently induce a long-term sustainable shift towards electricity generation from renewables. Finally, directions for future research are highlighted.

Contents

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1. Introduction

U.S. is the world's leading energy consumer [1] and utilizes resources in the form of fossil fuels, nuclear, and renewables to meet the demand for: (1) refined liquid fuels (gasoline and diesel) for the transportation sector; (2) electricity; and (3) heating/cooling. Fig. 1 displays the composition of U.S. energy supply by resource type. Fossil fuels (in the form of petroleum, natural gas and coal) account for 83% of the energy supplied to the U.S. economy in 2011 [1]. Nuclear power supplied 9% while the various renewable energy sources (including wind, solar, geothermal, hydropower, and biomass) contributed only 8% to the U.S. energy supply [1].

Electricity generation consumes the largest share of the U.S. energy resources. Fig. 2 displays the breakdown of U.S. energy consumption by demand sector. Generation of electricity utilizes 40%, refining of liquid transportation fuels consumes 29% while the combined demand for heating/cooling utilizes 31% of the U.S. energy supply [1].

There is growing public awareness that consumption of fossil fuels in large amounts is contributing to global warming by releasing increasing quantities of greenhouse gas emissions (containing carbon, sulfur and other atmospheric pollutants). In addition, extraction of large quantities of coal, natural gas, and crude oil are leading to faster depletion of the finite reserves of fossil fuels. The depletion of fossil fuels is likely to result in price fluctuations and uncertainties in the energy supply chain. Renewable energy sources have the potential to cost-effectively satisfy a large portion of U.S. electricity needs [2], while at the same time safeguarding the environment and reducing dependence on fossil fuels [3]. However, many obstacles exist that prevent the optimal utilization of renewables for electricity production. For example, in 2011 the total electricity generated in the U.S. was 4.5 million GWh, out of which only 11% was produced from renewable energy resources [4]. Research indicates that if optimally utilized, renewables can contribute 15% (or more) of total U.S. electricity generation by 2035 [1]. Therefore, research needs to be conducted to overcome the barriers.

This article analyzes how to improve and optimize the usage of renewables in the electricity sector, as it is the largest consumer of U.S. energy supply. The renewable resource potential, current usage, technical status, challenges, strategies, policies and assessment framework is discussed in the following sections.

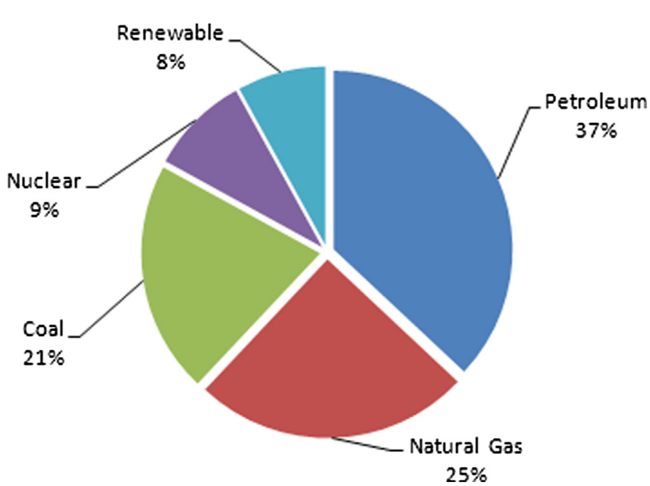


Fig. 1. Composition of U.S. energy supply by resource type [1].

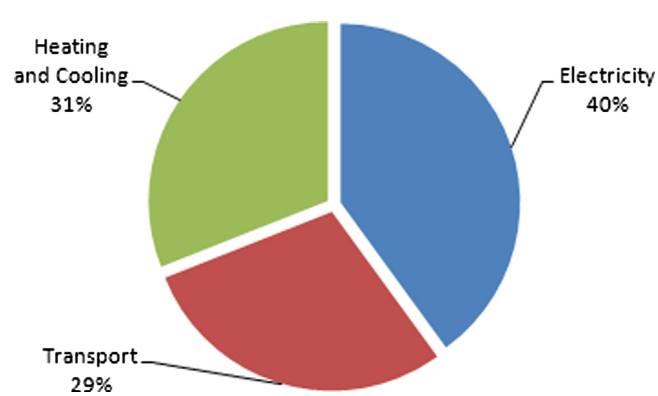


Fig. 2. Breakdown of U.S. energy consumption by demand [1].

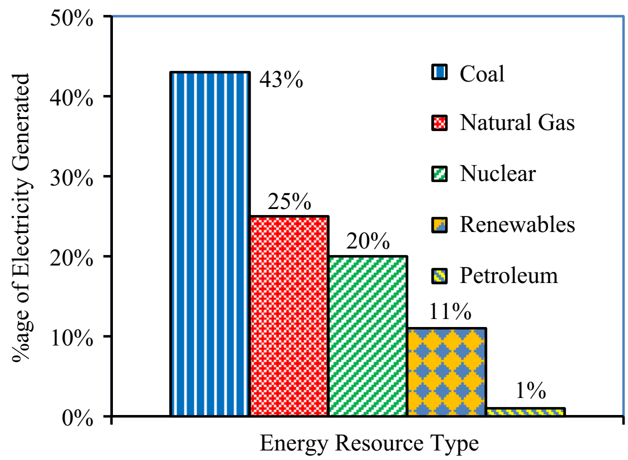


Fig. 3. Share of energy sources in U.S. electricity generation [4].

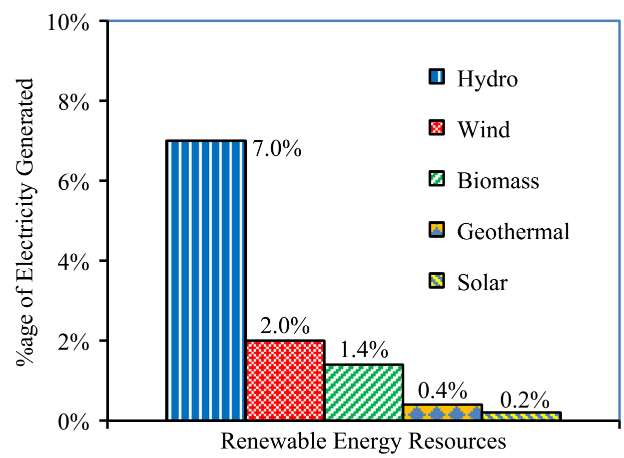


Fig. 4. Share of renewables in U.S. electricity generation [4].

2. Electricity generation from renewables in the United States: resource potential and current utilization

In 2011 the total electricity generated in the U.S. was 4.5 million GWh. Fig. 3 gives the share of the various energy resources towards U.S. electricity generation (in 2011), and shows that 11% was produced from renewables (including wind, solar, geothermal, hydropower, and biomass) [4]. Hydropower generated the maximum share of 7% and solar contributed the lowest share of 0.2% [4]. Fig. 4 gives the share of the various renewable resources in electricity generation.

Unlike liquid transportation fuels [5,6], there is no federal mandate that requires a minimum percentage of electricity to be generated from renewables [3]. However, varying level of mandated support is provided by individual states. As of 2011, 28 states have enacted binding renewable portfolio standards (RPS) that require power utilities to generate a minimum percentage of electricity from renewable resources (like solar and wind mandates in California) [1]. With the support provided by the various state level RPSs, projections indicate that renewables can contribute up to 15% of total U.S. electricity generation by 2035 [1]. The potential and current utilization status of various renewables used for electricity generation in the United States (as of 2011) is analyzed in the following sections.

2.1. Wind

The resource base of wind energy can be classified as either onshore or offshore [7,8]. In the United States, the estimated onshore wind energy has the annual potential to generate 50 million GWh of electricity [2], with the central areas (encompassing the states of Iowa, Kansas, Minnesota, Montana, Nebraska, North Dakota, Oklahoma, South Dakota, Texas, and Wyoming) having the largest potential as shown in Fig. 5 [9]. While the estimated offshore wind energy has the potential to generate 15 million GWh of electricity annually [2], with the New England and California coastal areas having the largest potential as shown in Fig. 6 [10].

In the U.S. wind power was used to generate ≈ 90000 GWh of electricity in 2011 [4]. Even though wind generated electricity currently makes up only 2% of total U.S. electricity generation, wind power has grown at a 25% annual rate (from 2001 to 2010) and represents 35% of all new generating capacity [1]. The growth in wind generating capacity is concentrated in the central states of Iowa, Minnesota, North Dakota, and Texas [1].

Onshore wind technology is generally considered to be commercially available in the U.S. [7]. Offshore wind technology faces some technical challenges associated with operating in a corrosive marine environment and installation of equipment at various water depths [8].

Electricity generation from wind takes place where and when the wind blows. This intermittency is perceived as an obstacle to the integration of wind generated electricity into the existing power grid and requires wind turbines to provide voltage control and grid support [7].

2.2. Solar

The southwestern states (of Arizona, California, Colorado, New Mexico, Nevada, Texas, and Utah) have the largest solar energy potential as shown in Fig. 7 [11]. The estimated solar energy resource base in the U.S. has the annual potential to produce 56 million GWh of generated electricity from photovoltaics (PV) or concentrating solar power (CSP) [2].

Total U.S. solar electricity generation installed capacity is ≈ 1 GW which was used to generate around 9000 GWh in 2011 [4]. The annual growth rate in U.S. electricity generation from solar power was 30% from 2001 to 2010 [1].

The current high cost of solar electricity is a major challenge. United States Department of Energy (DOE) is funding an initiative, known as the SunShot program, which aims to reduce the cost of solar electricity generation to less than $60/MWh [12]. While solar technologies are considered to be commercially available, a number of research and development work continue to be focused on improving conversion efficiencies and reducing electricity generation costs. Leveraging of storage mediums, demand response optimization, and other "smart-grid" technologies may further enable large-scale solar deployment by reducing systems costs [13–20].

2.3. Geothermal

The renewable resource base of geothermal energy can be classified as either conventional or enhanced geothermal systems (EGS) [22]. A conventional geothermal resource can run dry when most of the hot fluid has been extracted [22]. EGS strives to overcome the natural lack of hot fluid by pumping in water from an external source into the geothermal reservoir [23]. The estimated identified resources of geothermal energy has the potential to generate 0.1 million GWh of electricity annually, while the undiscovered resources of geothermal energy has a further potential to generate 0.6 million GWh of electricity annually [23]. Using EGS, the resource base is considerably enhanced and has the potential to generate 1.8 million GWh of electricity annually [22]. Fig. 8 displays the locations of identified geothermal sites (and the

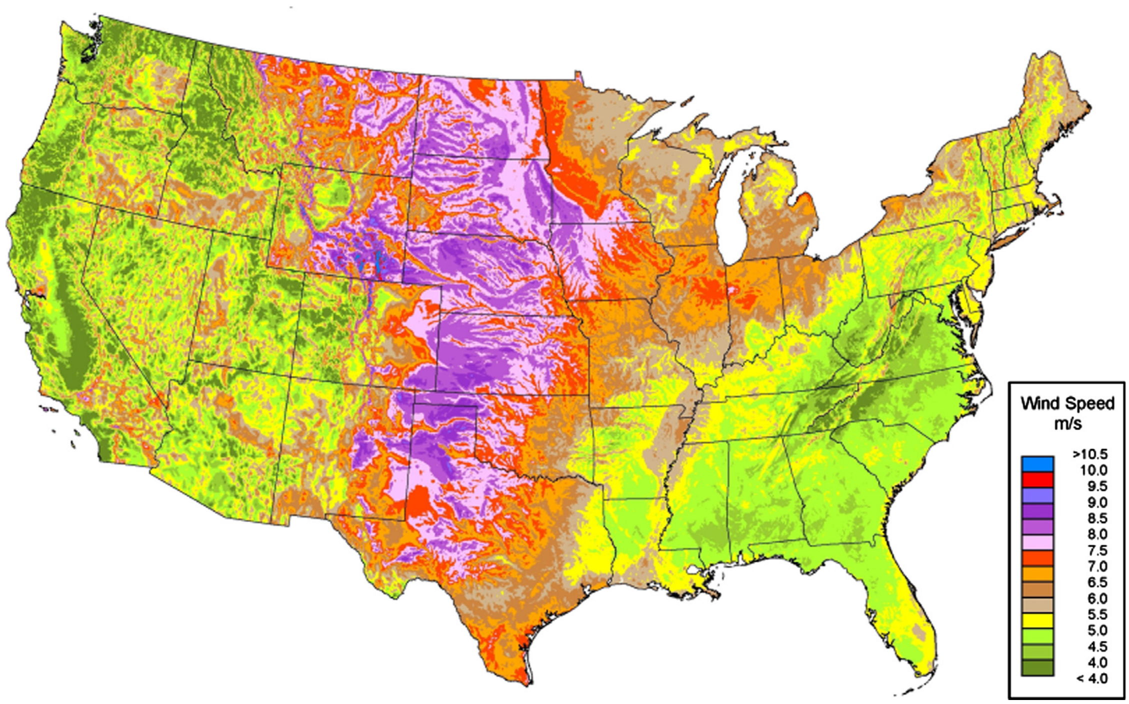


Fig. 5. U.S. onshore wind resources [9].

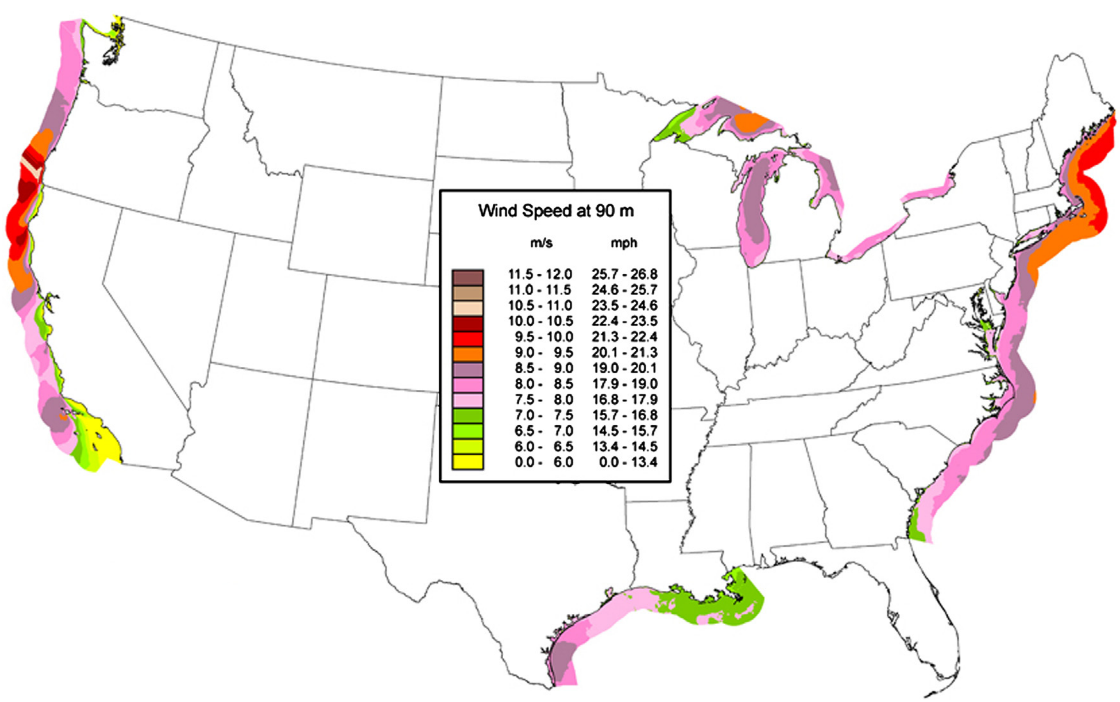


Fig. 6. U.S. offshore wind resources [10].

estimated potential for geothermal energy recovery using EGS) throughout the contiguous U.S. (excluding Alaska and Hawaii). The most promising areas are shown to be located in the western states (mainly in California, Idaho, Nevada, and Oregon) [21].

Total U.S. geothermal electricity generation installed capacity is ≈ 3 GW (with the bulk being located in the state of California) [1], which was used to generate 18000 GWh in 2011 [4]. Since 2000, the amount of electricity generated from geothermal resources has plateaued, indicating that most of the easily accessible geothermal sites in the U.S. have been tapped using conventional technology [4].

EGS technology can potentially enable large-scale deployment of economically recoverable geothermal electricity generation. However, EGS technology has not been demonstrated at scale and is not yet commercially available. The main challenge of EGS is developing technologies that can reliably achieve sufficient connectivity in fractured rock to yield economically feasible and sustainable production rates, without inducing significant

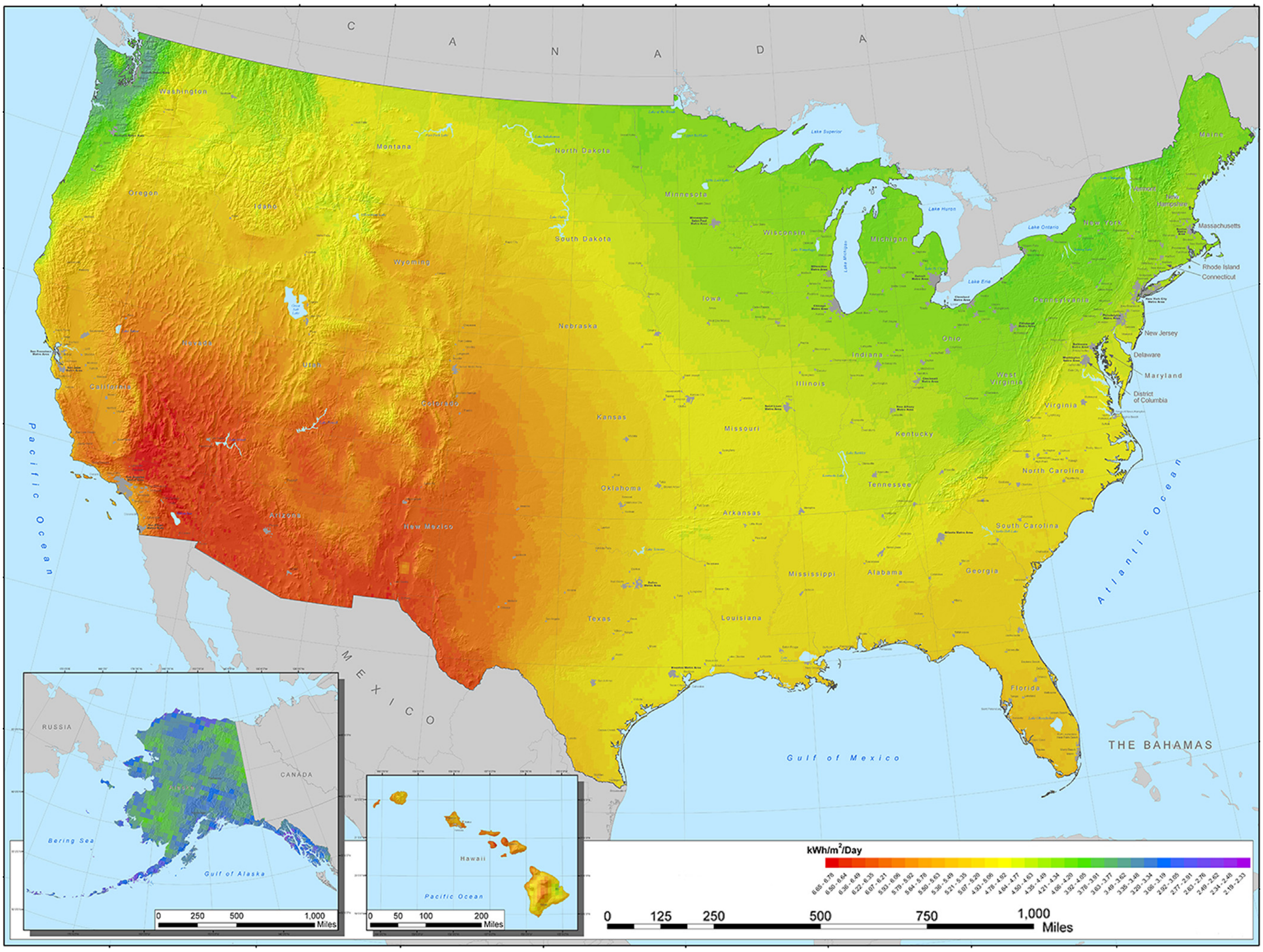


Fig. 7. U.S. solar resources [11].

environmental disturbances (e.g. risks of seismicity in the fractured rocks, and contamination of the water table) [23].

2.4. Hydropower

Due to the extensive river systems, the states located west of the Rocky Mountains (including Arizona, California, Colorado, Idaho, Nevada, New Mexico, Oregon, Utah, and Wyoming) have the best hydropower potential [24]. Fig. 9 provides information about the location of existing and potential hydroelectricity facilities in the contiguous United States [25]. After taking into consideration local land-use policies, regional environmental concerns, site accessibility, and power transmission, the total potential U.S. hydroelectric resource capacity is estimated to be 0.6 million GWh [26].

Hydroelectricity generation technology in the United States is fully commercialized with proven operational performance. In 2011, approximately 315000 GWh was generated from hydropower resources, making it the single largest source of renewable electricity production in the United States [4]. Currently, hydroelectric generation capacity (of 100 GW) represents 9% of the total U.S. electric generation capacity [1].

In the U.S., the use of hydroelectric resource has plateaued out, indicating that most of the promising large-scale hydropower sites in the U.S. have already been tapped [2]. Further growth is assumed to be largely dependent on low-head power [26], “run-of-the-river” projects and micro hydroelectric generation [27]. Currently only 3% of the 80,000 dams in the U.S. are used to generate electricity and represent a future potential source [28].

2.5. Biomass

Recent studies [30] have highlighted the potential availability of 1.3 billion tons per year of biomass for energy production (including electricity and liquid transportation fuels). The geographical distribution of the currently available biomass resource base in the contiguous U.S. is shown in Fig. 10 [29]. The identified biomass production areas include 450 million acres of agricultural land (mostly in the Midwest) which is 23% of the land area of the U.S., and 670 million acres of forestland (mostly in the Pacific Northwest), representing a third of the total land area of the continental U.S. [30].

In 2011 an estimated 63000 GWh [4] was generated in the U.S. using biomass (as a primary energy feedstock or as a secondary energy feedstock when co-fired with pulverized coal) [31], which represents 1.4% of total electricity generation and 16% of generation from renewables [4]. Combustion technologies used to convert biomass to electricity are generally considered commercial. Biomass procurement and feedstock quality are the key cost drivers that impact the cost of bioenergy [32].

Currently, biomass is the only renewable source that can be used to generate both electricity and produce liquid transportation

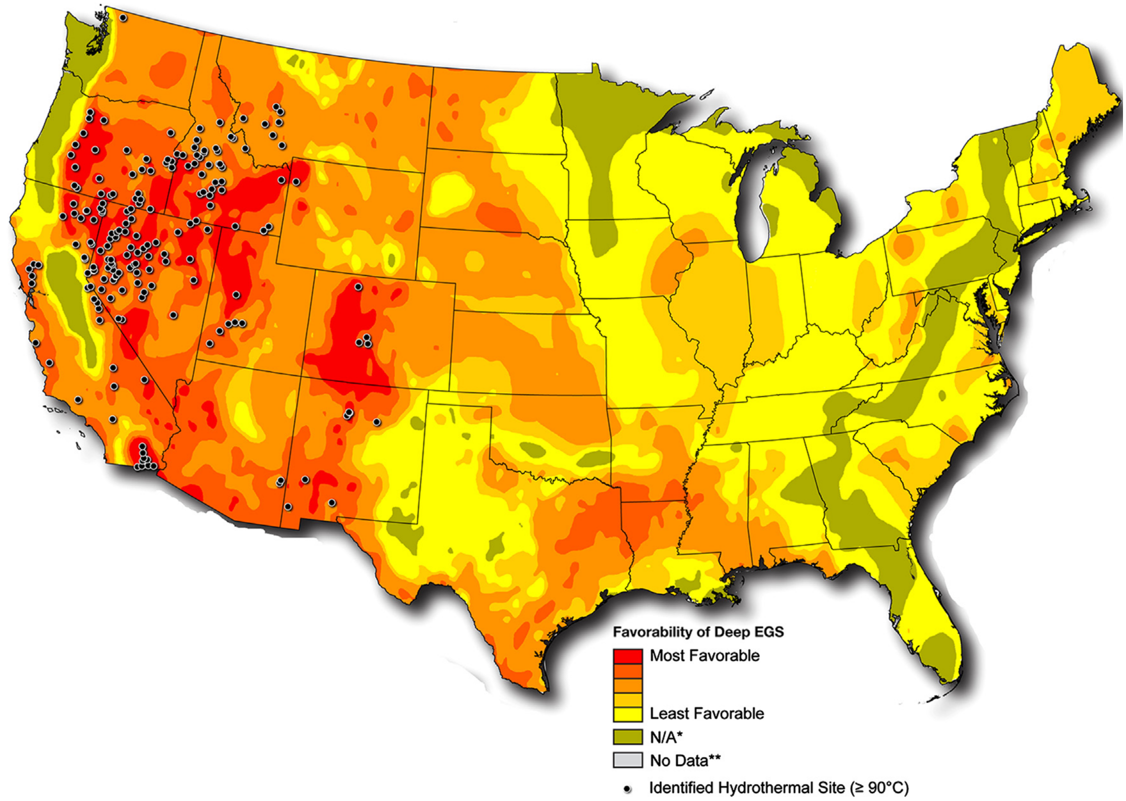


Fig. 8. U.S. geothermal resource [21].

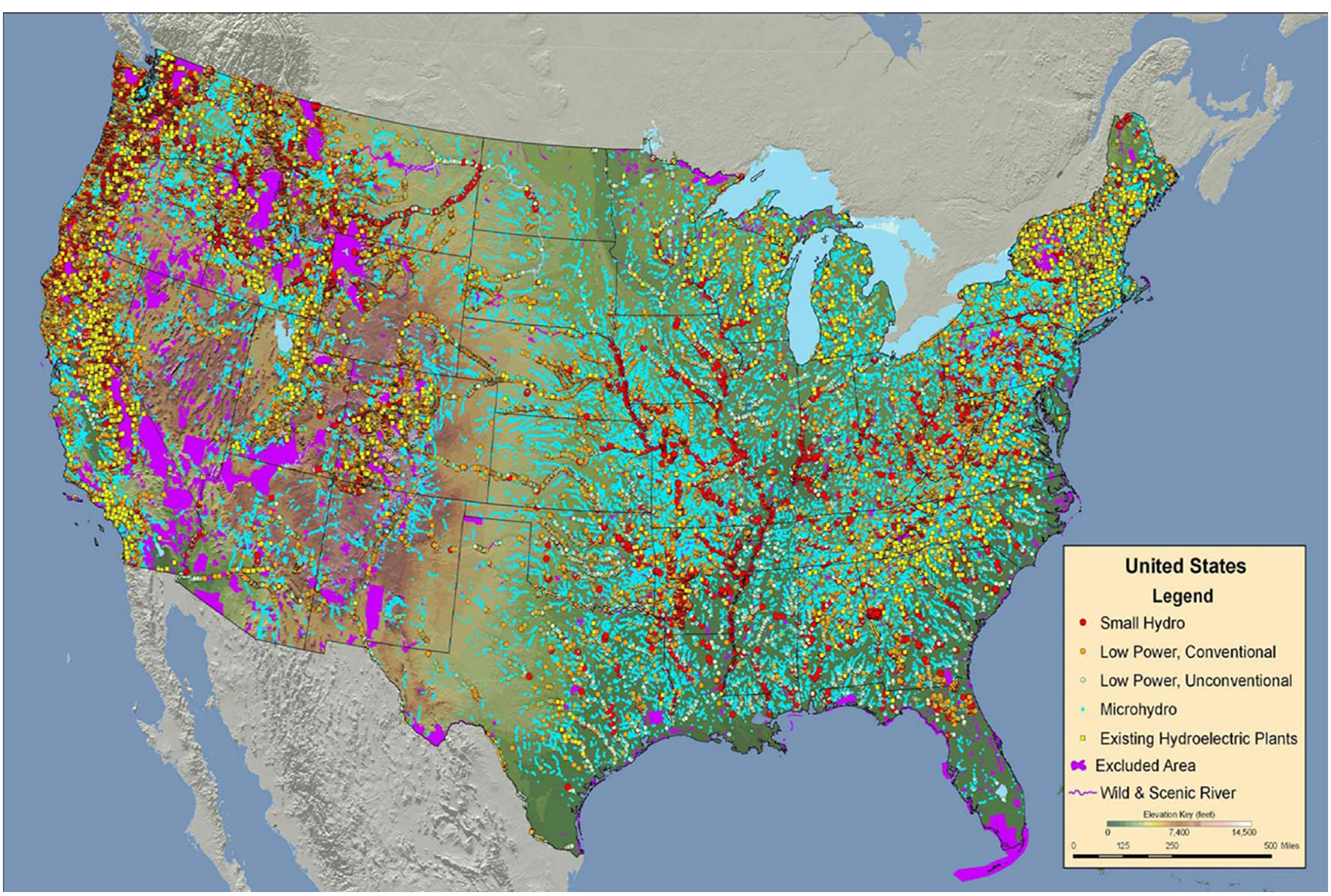


Fig. 9. U.S. hydropower resources [25].

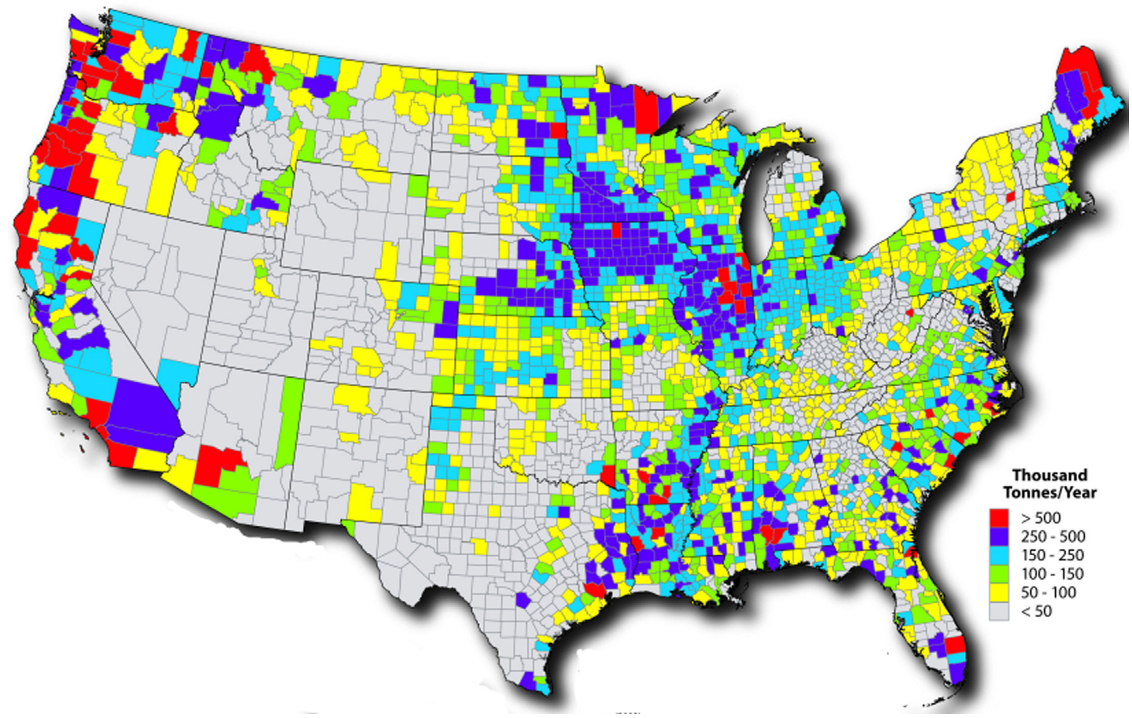


Fig. 10. U.S. biomass resources [29].

fuels [5], as such accurate estimates for biomass electricity generation potential are difficult to obtain but are estimated to be around 1.4 million GWh [1]. Due to the anticipated increase in the usage of biomass for production of liquid transportation fuels as mandated by the U.S. Renewable Fuel Standard [3], it is unlikely that in future, biomass can be relied upon as a major renewable source for U.S. electricity generation (except as a by-product from the refining of biofuels).

2.6. Status of renewable energy investment in the U.S.

Initial investment in the U.S. renewable energy sector was limited to begin with and gradually started to increase by the end of the 1990s. Since then, investments in renewable energy have significantly increased (by 61% over the period 2005–2010) to stand at $34 billion by the end of 2010 [33]. Wind energy attracted $15 billion, solar power received $9 billion, $6 billion was directed towards bioenergy, while other renewables (including geothermal and hydropower) accounted for $4 billion [33]. Fig. 11 shows the investment breakdown by type of renewable resource.

Although currently lagging behind wind power in total investments, the solar energy sector has recorded growth of almost 150% in installed generation capacity over the period 2005–2010. By 2050 the solar energy sector is expected to catch up with wind power (in both investments and installed capacity) and contribute equally towards renewable electricity generation and reduction in carbon emissions [33].

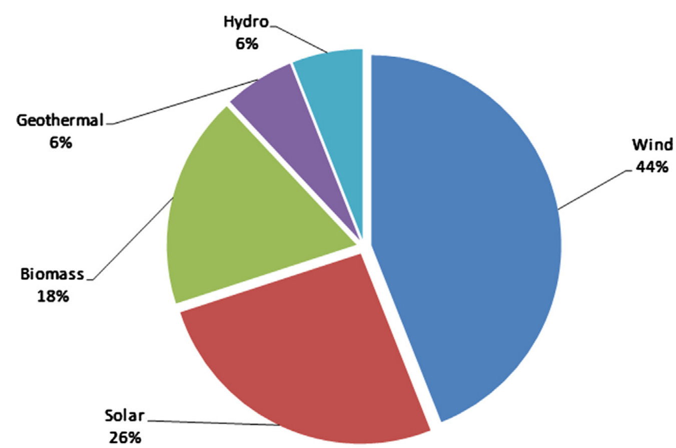


Fig. 11. Breakdown of investment in renewables by resource type [33].

2.7. Summary

The potential and current utilization status of renewables used for electricity generation is summarized in Table 1.

The distributed nature (i.e. low energy density) of renewable resources dictates that electricity generation facilities need to be located in close proximity to where the renewable energy resource occurs. Some renewables (like solar and wind) have an intermittent nature with varying time constants (e.g. when the wind is blowing) and cycles (e.g. when the sun is shining), which is perceived as an obstacle to electricity generation at a constant and predictable rate.

Renewable electricity generation technologies in general require high fixed capital costs (with long payback periods). All renewable technologies except for biomass-generated electricity [5] have no direct fuel costs and low operational costs. From a financial standpoint, the economies of scale inherent in large scale conventional electricity generation technologies (e.g. coal-fired and nuclear-powered plants) result in lower per unit electricity generation cost when compared to renewable technologies (with the notable exception of large hydro-electricity facilities). However, recent and continuous improvements in renewables technologies (particularly wind) demonstrate that renewables have the potential to compete with traditional electricity generation technologies on cost basis [1].

Table 1
Potential and current utilization status of renewables used for electricity generation in the U.S. [4].

Renewable type	Potential (million GWh)	Current usage (GWh)	Obstacles to growth
Wind	65.0	90,000	Distributed and intermittent nature, negative social impact, lack of grid integration
Solar	56.0	9000	High cost, distributed and cyclic nature, lack of grid integration
Geothermal	1.8	18,000	Lack of mature EGS technology, negative environmental impact
Hydropower	0.6	315,000	Negative environmental and social impact, most promising sites already exploited
Biomass	1.4	63,000	Incentive for biofuel production discourages use for electricity generation

3. Challenges preventing widespread deployment of electricity generated from renewables in the U.S.

Currently there are some challenges that prevent a widespread deployment of electricity generated from renewable resources. This section highlights the nature and scope of the challenges. By overcoming these hurdles, an increasing proportion of electricity generated from renewables can be used to meet the electricity demand in the U.S. [34–36].

3.1. High cost of electricity generation from renewables

Using current conversion technologies, the high cost of power generation is one of the major hurdles preventing widespread deployment of renewable electricity generation in the United States [2]. Some of the electricity generation technologies utilizing renewable resources (like biomass, wind, conventional hydropower and geothermal) are considered to be mature and can compete on per unit cost basis with traditionally generated electricity [1]. However, electricity generated from other renewable resources (like EGS and solar) cannot match the low per unit cost of electricity generated from traditional energy sources like fossil fuel (including coal and natural gas) and nuclear power [2].

It is essential that incremental learning curve based improvements continue to take place as far as the “mature” renewable generation technologies are considered [7,23,31]. Upcoming and under development renewable generation technologies will require sustained investment in research and development that might eventually lead to significant technological breakthroughs in conversion efficiencies (thereby drastically lowering the per unit generation cost to match those of traditionally generated electricity) [13,14,18,23].

3.2. Distributed nature of renewable resources

Per unit cost is not the only hurdle preventing widespread deployment of electricity generated from renewable resources [36]. The biggest challenge is how to efficiently and economically supply electricity from diverse and dispersed renewable generation sites to faraway electricity demand markets [37]. In the United States, most of the highest potential renewable resources are located in isolated and remote regions of the country [1]. For example, some of the highest solar energy potential is located in the sparsely populated southwestern desert states (of Arizona, New Mexico, Nevada, and Utah) [11]. However, the highest demand for electricity is located in the densely populated urban areas of the Northeast [4].

3.3. Negative environmental and social impacts

The negative impacts include but are not limited to extensive land usage (away from agriculture), and environmental degradation of areas of natural beauty. Wind farms are increasingly facing resistance from local communities concerned about the esthetic degradation caused by giant wind turbines that dominate the landscape [7], and the noise pollution associated with the constant whirring of turbine blades (that are audible up to a mile away from the generation site) [8]. In addition, bat and bird fatalities are also an area of growing concern when locating wind turbines [7,8]. Exploitation of geothermal resources can also lead to degradation of pristine wild life habitats (e.g. Yellow Stone National Park in Wyoming) along with environmental pollution caused by discharge of spent geothermal fluids [23]. A holistic approach will need to be devised in order to overcome negative environmental and social impacts (for details see Section 5).

3.4. Integration of electricity generated from renewables into the power grid

Electric supply can be sourced from power generation sites that are characterized by [38]: (1) being sited at dispersed geographical locations; (2) usage of a diverse mix of energy inputs (from renewables to fossil fuels). Demand for electricity can in turn be characterized by: (1) being concentrated in high population density areas; (2) being continuously varying according to spatial (north vs. south), seasonal (summer vs. winter), and temporal (day vs. night) fluctuations [39].

The basic function of the electric grid is to maintain an optimal balance between power supply and demand while at the same time maintaining transmission system integrity and ensuring distribution reliability [38]. Some of the challenges (that are preventing successful integration of electricity generated from renewables into the power grid) are outlined below.

3.4.1. Regulatory requirements for grid reliability

Autonomous grid operators are mandated by the U.S. federal regulatory authorities, to maintain and manage the electric grid system in their assigned regional zones [37]. Part of the mandate of power utility and grid operators is to ensure that transmission capacity is able to meet the demand for electricity in the assigned regional zones [40,41]. This is accomplished by having sufficient electricity transmission capability to cover emergencies (e.g. bypassing fallen transmission lines to maintain supply during a blizzard), in order to meet grid reliability criteria [40].

3.4.2. Maintaining diverse sources of electricity supply

Most of the power utilities source the bulk of their electricity demand from self-owned (or self-operated) power plants that use a variety of energy inputs (like coal, conventional hydropower, natural gas, and nuclear), while buying the remaining demand from independent power producers (including generators of electricity from renewables) [4]. The diverse supply mix is maintained so that the power utility is not dependent on electricity generated by a single power plant or only one type of energy input. This allows the electric grid to withstand the loss of the single biggest generating resource [36]. Due to the intermittent nature of some renewables (like solar and wind) [42], the generation and supply of electricity is not uniform and cannot be counted on to be available on-demand or to meet base-load requirements [43].

3.4.3. Requirements for reserve power generation capacity

For most power utility and grid operators, a 15% electricity generation reserve margin is sufficient to deal with contingencies without significantly affecting grid performance or system reliability [44]. Research has indicated that an electric grid can absorb significant amounts (up to 20%) of electricity generated from intermittent renewables if adequate reserve power generation capacity is available (to compensate for the times when the intermittent resource is not available for generating electricity) [45]. If the reserve capacity is dispatchable (like natural gas fired or hydropower), than the grid can incorporate an even higher fraction of renewable electricity (up to 40%) in the transmission network [46–49].

4. Strategies for increasing the feasibility of electricity generated from renewables in the U.S.

Due to the identified challenges in Section 3, strategies need to be formed that can be used to minimize costs, deal with the spatial nature of distributed renewables, and smooth temporal variations associated with intermittency [50].

4.1. Co-location of power generators

Most of the high potential renewable electricity generation resources are located some distance from the major electricity demand markets [1,4]. In order to increase the supply of renewable generated electricity, it might be necessary to upgrade the transmission lines (if they exist) between supply and demand sites so as to be able to cope with the additional electric load to be carried by the grid [51]. Upgrading the transmission capacity is not without significant cost and at the same time requires that normal grid operations be not significantly degraded during the upgrading process [51]. If no transmission lines are available between the supply-demand nodes, then costly new transmission lines will need to be laid before a renewable resource can start generating electricity [52].

Mainly as a result of the renewable portfolio standard (RPS) mandates [1], grid operators have to decide the optimal transmission capacity needed to economically and effectively distribute electricity generated from renewables [53]. If transmission line capacity is based on the maximum power generation potential of the renewable resource (i.e. electricity output at peak wind speeds or during maximum sunshine intensity), then due to the intermittent nature of renewables (like solar and wind) the transmission line will not be fully loaded apart from short durations of peak generation [54]. Conversely, if the transmission line is sized to align with average generating potential, than the renewable resource will not be able to take advantage of peak favorable conditions to generate at full potential [55]. Nevertheless, no transmission line dedicated solely to an intermittent renewable resource can be expected to operate with high utilization [56,57].

In supply chain logistics, the technique of variability pooling is used to reduce the overall system variability [54,58]. Along similar lines, power utilities and grid operators can reduce the temporal variation (associated with intermittent renewables) by co-locating a traditional power generator (e.g. using a dispatchable fossil fuel resource like natural gas) in close proximity to a renewable electricity generating resource (like solar or wind) [59,60]. This will go a long way to mitigate the temporal variation (associated with intermittent renewables) [54] by allowing a readily dispatchable generating resource to rapidly meet the electricity generation shortfalls [41,56]. In addition, the transmission line costs can be allocated across multiple (two or more) power generation sites in any given area [52]. However, it must also be noted that co-located traditional fuel power plants are unlikely to be situated near their resource base [46]. Trade-off analysis will therefore need to be carried out to weigh the perceived benefit of co-location against the increased fossil fuel transportation cost [59].

4.2. Leveraging electricity storage technologies

Electricity storage technologies can be leveraged to facilitate a greater deployment of intermittent renewable resources by smoothing the temporal variations (similar to the effect of co-location) and allow a greater percentage of the transmission capacity to be used [61,62]. In order to achieve a greater integration (say above 20%) of electricity generated from intermittent renewables, it will probably be necessary to utilize technologies that can store the excess electricity generated (during off-peak demand) for later use (during peak demand for electricity) when the intermittent renewable resource is not generating electricity (e.g. when the sun is not shining or the wind is not blowing) [63]. Some of the current and emerging electricity storage technologies and methodologies include: (1) deep-cycle batteries [64]; (2) compressed air energy systems [65]; (3) pumped hydro storage [65]; and (4) chemical conversion of electricity into hydrogen fuel [66,67]. However, none of the currently available storage technologies are economically and efficiently capable of providing long-term power storage without significant conversion losses [65,68].

The usage of electric cars is predicted to increase in the coming years [69] and can be expected to yield significant breakthroughs leading to increased battery storage capacity, longer charge holding time, and lower cost storage mediums [70]. Electric cars rely on batteries to store power, which is later used to operate an electric motor [71]. The batteries of electric cars are a potential source of electricity storage with the added benefit of being “non-stationary”, and can be recharged at multiple locations [72]. This flexibility can potentially be leveraged to maximize the usage of “battery farms” (that use the excess generated electricity to recharge batteries of electric cars) tied to urban renewable electricity generation from commercial roof-top solar panels and small-scale wind turbines [69,70,73]. Electricity storage capabilities embedded into a smart grid could also provide benefits to the transmission and distribution system [61,62].

4.3. Smart grids

Nowadays, the term “smart grid” is being used to describe the juxtaposition of centralized grid control systems with advanced communications capability over the entire electricity generation, transmission, distribution, and billing network [74]. Fig. 12 displays the schematics of a smart grid [75].

Smart grids utilize state-of-the art weather forecasting models to predict favorable generation conditions for wind and solar renewable resources [76]. This allows smart grids to anticipate the temporal fluctuations in the electricity generated from intermittent renewable energy sources [54,77]. Power generation from non-intermittent resources can then be optimized (by rapidly ramping production up or down) to meet expected and actual demand for electricity [78–80].

Smart grids use remote sensors located at generation sites, demand zones and embedded along the entire transmission network [81]. This real-time information allows smart grids to achieve and maintain an optimum balance between electricity demand and supply (over any given power distribution and transmission network) without having to rely on extensive reserve electricity generation capacity [82]. The ability of smart grids to do more with less generation resources means that a greater proportion of electricity from intermittent renewable resources can be

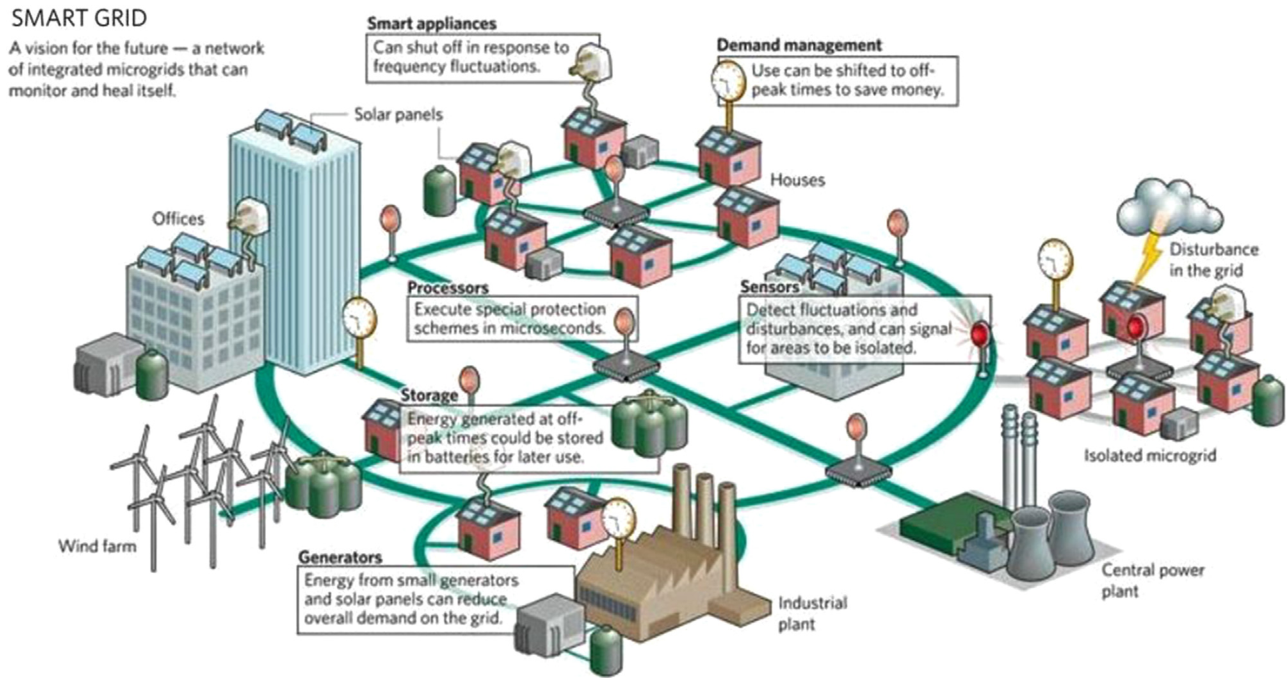


Fig. 12. Smart grid schematic [75].

integrated into the power grid without any adverse effect on transmission efficiency and overall system reliability [83].

4.3.1. *Smart meters*

Smart meters represent a set of technologies (and devices) that can enhance grid intelligence by monitoring, recording, and communicating the electricity generation and power consumption profiles of both producers and end-customers [84]. Smart meters have the capability to carryout billing with differentiated rates for peak (e.g. late afternoons) and off-peak (e.g. early mornings) demand hours [85]. Reduced costs offered by time-of-day pricing, provides end-users with an incentive to modify their electricity consumption habits (e.g. running the dishwasher at night) [86], which has the potential of reducing the overall power demand from the electric grid [85].

Another important feature of smart meters is the functionality of providing net metering for customers who generate (or receive) some part of their electricity consumption from site-installed renewable generators like residential or commercial roof-top solar panels [87]. Excess electricity generated by the customer is "sold" to the grid and the customer's account credited with the sold units. During times, when the on-site renewable resource is not generating electricity, the customer's draws power from the grid (and the account debited accordingly) [68]. Time-of-day pricing and net metering functionality of smart meters, can facilitate the integration of a greater proportion of electricity generated from intermittent renewables, and thus enable widespread deployment of distributed renewable resources [88].

5. Multi criteria sustainability assessment of renewable resource deployment

Future growth in electricity generation from renewable energy resources will largely be dictated by decisions made today regarding preferences in [89]: (1) optimal mix of renewable energy resource portfolio; (2) renewable electricity generation technologies (e.g. preferring solar PV over CSP); and (3) location of generation sites (e.g. medium wind quality areas near high demand zones vs. high wind quality areas in isolated regions).

In order to arrive at robust decisions (which cover a wide range of budgetary constraints and sustainability goals), it is important that these decisions be made while considering multiple criteria (and not just a single criteria like per unit generation cost) which gives a comprehensive assessment of each renewable energy resource. Therefore, sustainability assessment of renewable resource based electricity generation technologies is increasingly becoming essential when deciding upon the portfolio of renewable resources to be used for electricity generation [90,91].

Apart from the financial impact, assessment studies should also take into account the entire life cycle impact of a renewable electricity generation project (including portfolio of renewables being considered, choice of renewable generation technology, size of generator, quality of renewable resource at generation site, and distance of generator from the electric grid, etc.) on the environment (e.g. GHG emissions, land degradation, soil toxicity, and water pollution, etc.) and society (e.g. noise pollution and loss of esthetics from a wind turbine, or vast amounts of open spaces being dedicated for solar arrays, etc.) [92]. Literature review has identified some of the relevant sustainability indicators of renewable electricity generation technologies [89,93] which are discussed in the following sections.

5.1. *Cost of renewable electricity generation*

Input fuel cost is the major cost component of electricity generated from fuels like coal, natural gas, and biomass. Table 2 provides a summary of U.S. renewable electricity generation cost estimates.

While there is no "input fuel" requirement to generate electricity from renewable energy resources (except biomass), this does not mean that renewable electricity can be generated for "free". To get a true picture of the cost to generate one unit of renewable electricity, it is important to assess the total cost over the entire life cycle of a renewable electricity generation project. The life cycle cost includes manufacturing (e.g. cost to produce a solar panel), infrastructure (e.g. cost of drilling a recovery well at a

geothermal site), installation (e.g. cost to erect a wind turbine tower), operational (e.g. cost of biomass feedstock), and environmental (e.g. decommissioning cost at the end of the project life time). In addition, transmission costs of up to 1.5 cents/kWh [1] can be incurred if new transmission lines (or extensive upgrades) are required to connect the renewable generation site (e.g. wind energy farms located in isolated areas in the Midwest) to the electric grid. Literature review [94] indicates that for most renewable electricity generation technologies (with the exception of biomass), capital costs make up ≈ 95% of the life cycle cost.

The life cycle cost profile for the various renewable electricity generation resources is summarized in Table 3 and also analyzed below [2].

Wind: The lower end cost has been shown to be achieved by locating appropriate sized wind turbines in areas of consistently high wind speeds (e.g. wind generation sites in the state of North Dakota). At the lower cost range, wind generated electricity is competitive with electricity generated from fossil fuels.

Solar: Electricity generated from solar is the most expensive amongst all renewable resources. The wide range of per unit generation cost is mainly due to the varying conversion efficiencies of different types of solar PV panels and configurations of CSP arrays. Another factor impacting the cost is the intensity of solar radiation experienced by the geographic location (e.g. higher solar radiation intensity in Las Vegas vs. Boston) of the solar generating site, allowing favorably located solar renewable projects (both solar PV and CSP) to generate significantly more electricity using the same infrastructure and conversion technology.

Geothermal: The start-up cost of electricity generated from geothermal resources are highly dependent upon successful drilling of exploratory recovery wells (and injection wells for Enhanced Geothermal Systems), with multiple wells to be drilled in case of failure to recover the geothermal fluids at the first well site [95]. Research indicates that cost of drilling is on average 50% of the total capital cost for a geothermal project [96]. Despite the higher risk involved in the initial stage (i.e. drilling of exploratory wells), unlike intermittent renewables (like solar and wind), geothermal resource can predictably generate electricity (over sustained periods) and can be counted on to generate power to meet base-load electricity demand.

Hydropower: Electricity generated from conventional hydropower is the least expensive amongst all renewable resources. In hydroelectric projects, infrastructure (including dam construction and installation of turbines) costs make up the bulk of the total project costs. However once commissioned, hydroelectric power projects require low running costs and long project life time [97]. Hoover dam (Nevada, USA) was commissioned in the 1930s and is still generating electricity.

Biomass: Electricity generated from biomass is considered competitive with electricity generated from natural gas and coal. Biomass power projects do not require substantial upfront capital costs as compared to other renewable resources (e.g. solar), and follows the same cost profile as fossil fuel power projects [98]. This is due to the fact that the operational fuel costs are significant, requiring procurement of biomass feedstock (which unlike solar and wind energy is “not free”).

Table 2
U.S. renewable electricity generation cost estimates [1,2].

Renewable resource	**Wind**		**Solar**		**Geothermal**		**Hydro-power**		**Biomass**	
Estimate range	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
Cost ($/kWh)	$0.08–0.34		$0.16–0.64		$0.09–0.12		$0.06–0.11		$0.10–0.13	

5.2. Environmental impacts

The environmental impact of electricity generation (from renewable resources) includes but is not limited to: (1) biodiversity concerns; (2) GHG emissions; and (3) water usage. Table 4 gives the life cycle environmental assessment of electricity generation from renewable resources.

The popular belief is that there are no GHG emissions when electricity is generated from the so-called “clean” renewable resources like hydropower, solar, wind (but not including biomass and

Table 3
Life cycle cost assessment of electricity generation from renewable resources.

Cost component	**Wind**	**Solar**	**Geothermal**	**Hydropower**	**Biomass**
Operational ($/kWh)	N/A	N/A	N/A	N/A	Feedstock
Manufacturing ($)	Turbine, blades and tower	PV panels and parabolic troughs	Power plant turbine		
Infrastructure ($)	Land	Land	Recovery well drilling, and land	Dam, water reservoir, and land	N/A
Installation ($)	Wind turbine tower erection	Solar arrays, and molten salt storage (for CSP)	Installation of power plant and accessories		
Transmission ($/kWh/mile)	Laying of transmission lines and distance from nearest grid connection				
Decommissioning ($)	At the end of the project life time				

Table 4
Life cycle environmental assessment of electricity generation from renewable resources.

Environmental impact	**Wind**	**Solar**	**Geothermal**	**Hydropower**	**Biomass**
Biodiversity concerns	Collision fatalities of birds and bats	Plant community change due to shading effects	Surface disposal of brine fluids	Habitat loss through inundation	Soil degradation
GHG emissions	During the manufacturing of the wind turbine	During the manufacturing of solar panels and parabolic troughs	Surface disposal of geothermal fluids	During dam construction	During feedstock combustion
Water usage	During the manufacturing of the wind turbine	During the manufacturing of solar panels and parabolic troughs	Reinjection of water to refresh the geothermal reservoir (for EGS)	During initial filling of the reservoir	For steam generation and cooling purpose

geothermal). This is not a true assessment of the environmental impact caused by electricity generated from renewable resources. Most renewable technologies do not emit carbon dioxide equivalent (CO_{2-e}) emissions during electricity generation, but this does not mean that there are no significant GHG emissions over the entire life cycle of the renewable technology. For most renewables, the GHG emissions are "back loaded" and occur during the manufacturing and installation phase, instead of occurring during the operational phase (i.e. being "front loaded"). The exceptions are biomass (and possibly geothermal) technologies that are more like conventional technologies (using fossil fuels) in emitting significant CO_{2-e} emissions during the electricity generation phase (e.g. combustion of biomass to produce heat and steam for power generation). However, the environmental impact is not limited to GHG emissions. Another factor that impacts the environment is the water usage requirement to generate electricity from each renewable resource [89].

The life cycle GHG emission and water usage for the various fossil fuel and renewable conversion technologies (in the U.S.) are displayed in Tables 5–6 and analyzed below.

Wind: Most of the GHG emissions result during the manufacturing of the wind turbine and tower, while very little emissions occur during the operational power generation phase. Some water is used in the manufacturing of wind turbines (and towers), however very little water is consumed during the actual on-site operation of the wind turbine [105].

Solar: The GHG emission profile for solar is similar to that of wind, with very little emissions occurring during the operational power generation phase. Most of the GHG emissions occur during the manufacturing of the solar PV panels and parabolic troughs (for CSP). However the manufacture of solar PV panels is energy intensive [101]. Although the values are higher than those associated with wind, the emissions are still lower than those from fossil fuel technologies [103].

Although water is used in the manufacturing of solar PV panels (and parabolic troughs), very little water is consumed during the actual on-site operation of the solar PV panels [106]. However, CSP technologies that utilize a central tower have significant water usage for cooling purposes [107], which might be a limiting factor as some of the best CSP sites are located in the arid desert areas of the southwestern United States [11].

Geothermal: A wide range is observed in CO_{2-e} emissions from geothermal systems [102], mostly due to the result of the choice of generation technology used (conventional geothermal or EGS). In conventional geothermal systems, the "spent" geothermal fluids (hot water, steam, and waste gases) are disposed off outside the recovery well and can result in significant GHG emissions [108]. However in EGS, the "spent" geothermal fluids are injected back to refresh the geothermal reservoir and results in significantly lower GHG emissions [109].

Water usage by geothermal systems can be very extensive depending upon the nature of the technology (conventional geothermal vs. EGS), however irrespective of the technology, all geothermal systems require substantial water for cooling purposes [107]. Conventional geothermal systems depend upon the geothermal fluids naturally present inside the reservoir and thus require very little extra water to recover the heat for power generation. The total life cycle water usage requirement for conventional geothermal systems is comparable to solar [104]. However, EGS requires large quantities of water to be pumped back into the reservoir (via an injection well) to refresh the geothermal reservoir. Researchers have indicated that the total life cycle water usage requirement for EGS are significantly more than the requirement for conventional fossil fuel generation technologies [104].

Hydropower: The GHG profile for conventional hydropower indicates that significant emissions occur both during the dam construction and subsequent power generation phase [103,110]. Although the GHG emissions during the construction phase are understandable, it might seem counter-intuitive that emissions occur during the operational phase where potential energy of the discharged water (from the reservoir) is used and no "fossil fuels" are combusted. However, it is important to remember that water reservoirs (associated with hydroelectric projects) are created as artificial lakes by the submersion of vast areas of previously open land [111]. Over the life cycle of the dam, anaerobic decomposition of the submerged biomass (e.g. grasses, tress, vegetation, etc.) will continually release methane emissions (which have a global warming potential 25 times higher than carbon dioxide emissions) [112].

As the name suggests, hydropower by nature uses water to generate electricity. However there is ongoing debate whether water is actually consumed during electricity generation. Some researchers are of the view that significant amounts of water evaporate from the surface of dam reservoirs and should be counted against the life cycle water consumption. On the other hand, researchers argue that water also evaporates from naturally free flowing rivers, and as such should not be counted as consumption but rather as water withdrawal which is returned back after discharge from the reservoir [113].

Biomass: Similar to conventional electricity generation (using fossil fuels), biomass feedstock's (e.g. crop residue, perennial grasses, wood, etc.) release CO_{2-e} emissions during combustion. However, researchers are of the view that electricity generated from biomass is "carbon neutral" as combustion of biomass only releases carbon dioxide that was removed from the atmosphere (by photosynthesis) during the cultivation of the biomass feedstock [114].

Water requirements for biomass generated electricity are twofold. At the front end is the water requirement for steam generation and cooling purposes during electricity production. In this regard the water requirement is very similar to conventional fossil fuels [104]. However at the back end, significant water usage is required during the cultivation of the biomass feedstock. Some biomass feedstocks like perennial native grasses and forests do not require additional water other than that received from natural precipitation (rainfall and snowfall). While on the other hand, commercially cultivated biomass feedstocks (like food grains and crop residue) require significant amount of irrigation water

Table 6
Life cycle water usage of U.S. electricity generation from fossil and renewable resources [104].

Generation resource	Coal	Natural gas	Wind	Solar	Geothermal	Hydro-power	Biomass
Water Use (kg/kW h)	80	80	1	10	10–300	36	80

Table 5
Life cycle carbon emissions of U.S. electricity generation from fossil and renewable resources [99–103].

Generation resource	Coal	Natural gas	Wind	Solar	Geothermal	Hydro-power	Biomass
$C0_{2-e}$ emissions (g/kW h)	1000	540	25	90	170–800	109	0

(depending on the type of crop and geographical location) which can be drawn from a number of freshwater resources (e.g. lakes, rivers, etc.) [98].

5.3. Social impacts

There are a wide range of social impacts (both positive and negative) that result from electricity generation from renewables. The positive social impacts range from [92,115]: (1) energy security—by lessening dependence on imported fossil fuels; (2) enhanced access to electricity—for remote areas faraway from electric grids; (3) economic stimulation and job creation in under developed rural areas; and (4) reduction in GHG emissions. Table 7 lists the concerns of social impact of electricity generation from renewable resources.

The land usage associated with each renewable resource is summarized in Table 8 and analyzed below.

Wind: Due to the dispersed nature and low energy-density of wind power, the land usage requirements are extensive if land is dedicated solely for a wind farm [92]. However, once a wind turbine is installed it is not disruptive and lends itself for dual use of land for agriculture, which has the potential to reduce the actual footprint. Wind farms are also increasingly facing resistance from local communities concerned about the esthetic degradation caused by wind farms where giant wind turbines dominate the landscape, and the noise pollution associated with the constant whirring of turbine blades that are audible up to a mile away from the generation site [118].

Solar: Power generation requires extensive land usage for setting up of solar arrays if land is dedicated solely for solar power generation [115]. However, solar does not suffer from the same esthetic image problem as wind. The reasons are twofold: (1) solar PV panels are generally installed on roof-tops (both residential and commercial buildings) and thus require very little extra land; (2) CSP systems have extensive land usage but are generally located in sparsely populated arid desert areas (e.g. Nevada Solar 1 project is located in the desert outskirts of Las Vegas). As such, installation of solar generation projects does not displace any current productive activity from the project site.

Geothermal: Strictly speaking the above ground land usage is modest as the geothermal reservoir is situated underground. However due to the risk of land subsidence (due to the drilling and natural seismic activity), it is advisable to include the entire geothermal field for calculating land usage [89]. In addition, the negative social impacts are extensive. They range from increase in the frequency (but not magnitude) of seismic activity (mostly associated with EGS) [119], and improper disposal of the spent geothermal fluids which are often foul smelling (due to the presence of H_2S and NH_3) [89].

Hydropower: The land requirement for hydropower projects generally depend upon the size of the dam reservoir. In recent years construction of new hydroelectric projects in the U.S. is limited by two main facts: (1) most of the best sites have already been developed; (2) increasing social pressure from local communities concerned about the impact of dam construction on submersion of agriculture land, displacement of people (and livestock), loss of natural habitat, and restriction of natural flow of rivers [120]. It is expected, that future hydropower projects will be limited to micro-scale or upgrades (and expansions) to existing large-scale hydropower projects.

Biomass: The land usage requirements for growing the biomass feedstock are varied. The increasing use of biomass as source for energy generation has resulted in an ongoing debate regarding the “food vs. fuel” aspect [114]. However, the emphasis is more on usage of biomass feedstock for production of liquid transportation fuels and the use of food grains like corn and soybean for the production of ethanol and biodiesel respectively [98]. Biomass feedstocks used for electricity generation for the most part are composed of non-food grains (like municipal solid waste, crop and forest residues, etc.) requiring no direct land usage [5].

6. Renewable energy policy for the United States

6.1. Evolution of the current U.S. renewable energy policy

Early renewable energy projects (circa 1980s) in the U.S. were supported by investment tax credits that were based on installation (rather than performance) which resulted in issues of low productivity and unreliable equipment [1]. The investment tax credits expired in 1986, which forced investors to focus on improving the reliability and efficiency of renewable electricity generation technologies [1]. The 1990s realized a new type of tax credit, called the production tax credit, which propelled technological improvements in electricity generation from renewables and further encouraged investors to focus on electricity output (rather than installation) [1].

6.2. Recommendations for optimizing future U.S. renewable energy policy

This section recommends a number of rigorous policy instruments that can be used for optimizing future U.S. renewable energy policy (by overcoming some of the major financial, political, regulatory, and technical hurdles). Literature review highlights the importance [121–124] and effectiveness [125] of intervention by the U.S. federal government in order to achieve a sustainable shift towards electricity generation from renewables.

Table 8
Land usage of U.S. electricity generation from renewable resources [92,110,115–117].

Renewable resource	Wind	Solar	Geothermal	Hydro-power	Biomass
Land usage (km^2/TW h)	70	30–65	20–75	70–750	N/A

Table 7
Concerns of social impact of electricity generation from renewable resources [92,115].

Social impact	Wind	Solar	Geothermal	Hydropower	Biomass
Health concerns	Nuisance from noise and flickering	N/A	Hydrogen sulfide emissions	Water-borne diseases	Exposure to pesticides
Impact on local economy	N/A	N/A	N/A	N/A	Economic stimulation of rural areas
Land usage	For siting wind turbines and tower	For siting solar arrays	For drilling recovery and injection wells	For reservoir and dam construction	N/A

Some of the key policy instruments identified through literature review are detailed in the following sections.

6.2.1. Reduce the fluctuations and uncertainties in tax incentives

A major issue that has affected the renewable energy industry is the fluctuating nature of federal tax incentives (specially the production tax credit for electricity generated from renewables). This has resulted in the renewable electricity industry enduring continuous financial uncertainties. Encouraging sustained investment in new renewable energy initiatives will require a stable tax incentive policy with a long time horizon [122,123].

6.2.2. Equitably distribute subsidies for electricity generation technologies

Fig. 3 (Section 2) shows that renewables contribute 11% of U.S. electricity generation while the share of conventional energy sources (including fossil-fuel and nuclear) is 89%. However, renewable technologies only receive 6% (while conventional technologies get 94%) of the subsidies from the U.S. federal government for the generation of electricity [126]. The purpose of subsidies is to provide support for emerging electricity generation technologies during their formative years. Despite the fact that electricity generation from conventional technologies (including nuclear and fossil-fuel based) is well established for more than a century (since 1960s in case of nuclear), they continue to receive substantial subsidies in order to safeguard the supply of so-called “cheap and reliable” electricity for industrial and residential consumers. These subsidies include but are not limited to the following [121]: (1) preferential tax regimes and rebates; (2) exemptions from certain environmental regulations during operations and decommissioning; (3) undertaking of legal liabilities by the federal government for nuclear power; and (4) generous R&D funding for mature technologies.

The combined effect of these subsidies is to encourage irrational use of electricity (leading to over consumption) by hiding the true cost of electricity generation from consumers. In addition, subsidies distort market competition by giving conventional generation of electricity an unfair advantage over renewable generation [121]. Some researchers propose a policy whereby, subsidies for conventional technologies and mature renewables (i.e. large-scale hydro and onshore wind power) are eliminated or gradually withdrawn [121]. Politically it will be difficult for the U.S. federal government to completely eliminate subsidies for mature technologies [2]. It is therefore recommended that the subsidies received by various electricity generation technologies be gradually brought in line to reflect their actual share in electricity generation. This will result in renewables receiving almost double their current level of subsidies (i.e. 6% vs. 11%) which will go a long way in increasing the deployment of renewables for electricity generation.

6.2.3. Include environmental cost in the retail price of electricity

Currently the retail price cost of electricity does not take into account the cost of carbon emissions during electricity generation. The U.S. federal government can play a role in accomplishing a sustainable shift towards renewable electricity by imposing a tax on carbon emissions, thereby increasing the cost of electricity generated from fossil fuel (i.e. coal, petroleum, and natural gas). Alternatively, the government could set a cost on carbon via a cap-and-trade system whereby firms are allowed to buy and sell emissions credits in the marketplace; this “tax-free” model (based on the polluter pays principle) of distributing tradable pollution rights has become politically popular, especially after its documented success in reducing other pollutants, namely sulfur dioxide and nitrous oxide, in the United States [127]. Emissions trading schemes by way of the Regional Greenhouse Gas Initiative (RGGI) of “carbon tax” adopted by 9 Northeastern states (including major industrial states like New York and New Jersey) in the U.S. [128–130] have shown to be effective in reducing annual carbon emissions by 23% (in 2011 compared to emission levels before the start of the program in 2008). Studies show that a national level carbon tax of $20/ton of carbon dioxide equivalent emissions would raise $1.25 trillion over a 10-year period [129]. Revenue from such a tax could be used to promote and establish renewable-energy projects.

6.2.4. Implement a national feed-in tariff (FIT)

A number of researchers [121,124,131] advocate the enactment of a national feed-in tariff which will aim to stimulate deployment of renewables by guaranteeing a selling price (over a fixed time horizon of 15–20 years) for the generated electricity. The rationale behind this scheme is to mitigate the current risks (i.e. fluctuating government incentives and spot price of electricity) associated with investment in renewable energy resources.

FITs place a legal obligation on utilities to buy electricity (from renewables) generated within their geographic and regulatory service zones. In addition, utilities are also required to guarantee grid access (to renewable electricity producers) by absorbing the costs associated with grid connectivity (i.e. enhancement of existing transmission capacity or installation of new transmission lines where none currently exist) and net metering. Under a FIT regime the sale price of electricity is guaranteed but is not constant (i.e. tariff gradually declines over the contract period), nor is the tariff required to be the same for each type of renewable resource (e.g. differentiation allowed between solar and wind, etc.). FIT schemes have shown to be successful in Germany [132] and Canada [131] as it provides renewable electricity producers a stable and year-round cash flow. Production tax credits (PTC) on the other hand can only be claimed annually when filing tax returns.

6.2.5. Mandatory Green Power Option (MGPO)

The mandatory green power option (MGPO) is a market-based policy which requires utilities to offer consumers the option of buying higher priced electricity (generated from renewables) as a way to sustain renewable technologies and to show commitment to environmental causes [133]. MGPO has been shown to be effective in increasing (by up to 2%) the deployment of all types of renewables for electricity generation [125,134–136] through consumers' willingness to pay premium prices in order to support green-power.

6.2.6. Enact a national level Renewable Portfolio Standard (RPS) for the U.S.

By 2011, 28 states have enacted binding Renewable Portfolio Standards (RPS) for generation of electricity from renewables. Table 9 summarizes the binding RPS requirement for each state, including [133]: (1) target year when the RPS becomes binding; (2) percentage of electricity to be generated from renewables; (3) list of eligible renewables under the RPS; and (4) installation and production incentives (including but not limited to tax credits and rebates).

Some states have adopted a “voluntary” RPS which is non-binding (i.e. there are no legal or financial sanctions if by the desired date the utilities fail to generate the targeted amount of electricity from renewables). For instance, the state of Utah has adopted a “voluntary” target of 20% electricity generation from renewables by 2025. The voluntary nature of the RPS means that Utah (which is ranked in the top 10 states by solar energy potential [11]) has only managed to install 5 MW of electricity generation

Table 9
Binding Renewables Portfolio Standards (RPS) in different States of the U.S. for electricity generation [133].

State	Year[a]	Amount[b] (%)	Eligible renewables	Rebates and tax incentives
Arizona	2025	15	Hydroelectric, geothermal, solar, wind	$0.01/kW h (paid for 10 years)
California	2010	20	Hydroelectric (small scale), geothermal, solar, wind	$0.017/kW h paid for 20 years
Colorado	2020	20 (4% from solar)	Hydroelectric (small scale), geothermal, solar, wind	Solar: $0.11/kW h (paid for 20 years) for systems < 3 MW installed capacity
Connecticut	2020	20	Hydroelectric (small scale), solar, wind	$0.3/kW h (for 6 years) for systems with installed capacity between 1 and 10 kW
Delaware	2019	20 (2% from solar)	Hydroelectric (small scale), solar, wind	$0.19/kWh for systems with installed capacity between 0.5 and 50 kW
Hawaii	2020	20	Solar, wind	30% of installation cost
Iowa	2020	20	Hydroelectric, solar, wind	$0.01/kW h, paid for 10 years 15% of the installation cost
Illinois	2025	25 (19% from wind)	Hydroelectric, solar, wind	25% of project costs or $0.5 M Solar: $0.2/kW h up to170 MW h
Maine	2017	30	Hydroelectric, geothermal, solar, wind	$0.5/kW h for systems > 1 MWh with a maximum rebate of $4000
Maryland	2022	10 (2% from Wind)	Hydroelectric (small scale), geothermal, solar, wind	$0.0085/kW h, with total rebate of $2.5 M Solar: $0.20/kW h, no limit
Massachusetts	2009	4	Solar, wind	Solar: $0.55/kW h for systems < 6 MW Wind: $5.2/W with max of $0.13 M
Minnesota	2025	25	Hydroelectric (small scale), solar, wind	$0.01/kW h, paid for 10 years
Missouri	2020	11	Solar, wind	None
Montana	2015	15	Hydroelectric, geothermal, solar, wind	15% of installation cost
New Hampshire	2025	16	Hydroelectric (small scale), geothermal, solar, wind	$0.75/W for systems < 100 kW (lesser of 25% of total cost or $50,000)
New Jersey	2021	23	Hydroelectric, geothermal, solar, wind	Solar: S0.4/MW h, paid for 15 years
New Mexico	2020	20	Hydroelectric, geothermal, solar, wind	Wind: $0.01/kW h; Solar: $0.027/kW h (10 year period for systems > 1 MW)
Nevada	2015	20 (5% from Solar)	Hydroelectric, geothermal, solar, wind	Hydroelectric: $2/W; Wind: $2.15/W; Solar: $1.35/W (for systems < 1 MW)
New York	2013	24	Hydroelectric, solar, wind	50% of installed cost for system < 50 kW
North Carolina	2021	13	Hydroelectric, geothermal, solar, wind	35% of installed costs (max of $2.5 M)
Oregon	2025	25	Hydroelectric (small scale), geothermal, solar, wind	Solar: $0.0856/kW h for 10 years (systems sized 10–200 kW)
Pennsylvania	2020	19 (1% from Solar)	Hydroelectric (small scale), geothermal, solar, wind	Solar: $0.15/kW h plus 35% of installed costs for systems < 3 kW
Rhode Island	2020	15	Hydroelectric (small scale), geothermal, solar, wind	Solar: $0.3 kW/h; Wind: $0.25/kW h (15 year period for systems < 5 MW)
Texas	2015	25	Hydroelectric (small scale), geothermal, solar, wind	10% of installed costs
Vermont	2013	10	Hydroelectric (small scale), solar, wind	Solar/Wind: 7.2% of installed cost Geothermal: 2.4% of installed cost
Virginia	2022	12%	Hydroelectric, geothermal, solar, wind	$0.037/kW h for 20 years. Eligible system size is between 50 kW and 20 MW
Washington	2022	15	Hydroelectric, geothermal, solar, wind	$0.12/kW h with max payment of $5000
Wisconsin	2015	10	Hydroelectric, geothermal, solar, wind	Solar: $0.25/kW h for systems < 10 kW

[a] Date when the full RPS target becomes binding.
[b] Percentage of electricity that must be generated from renewables.

capacity from solar [4] (and is ranked 30th in the nation in solar electricity generation capacity in 2011). The RPS is binding in the neighboring state of New Mexico (also ranked in the top 10 states by solar energy potential [11]) and results in the installation of 120 MW of electricity generation capacity from solar [4] (and is ranked 4th in the nation in solar electricity generation capacity in 2011).

This implies that binding RPSs are more effective (than voluntary ones) in promoting the deployment of renewables (for electricity generation in the U.S.) due to the “carrot” of rebates (on installation costs) and tax incentives (for electricity production from renewables), along with the “stick” of the mandatory minimum amount of electricity that has to be generated from renewables [125,135,136].

Binding state level RPSs have shown to be effective in increasing the penetration of all types of renewables for electricity generation [125,134–136] and the reduction in GHG emissions [129,130]. RPS mandates that provide tax credits or rebates (both direct and indirect) on installation costs (for renewable electricity generators) have shown to have a significant effect on lowering the cost of renewable electricity [137].

Table 9 also shows that the different state level binding RPSs are not uniform and have differing priorities, standards, goals and requirements. As a result the deployment of renewables (for electricity generation) has not been proportionate (to their potential) across the different states. For example, the state of Iowa has a target of 20% electricity generation from renewables by 2020. Iowa offers tax incentives of $0.01/kWh for electricity generated from renewables (paid for 10 years), plus a rebate covering 15% of the project installation cost. As a result, Iowa (while ranked 7th in the nation in wind energy potential [9]) has managed to install 4500 MW of electricity generation capacity from wind [4] (and is ranked 3rd in the nation in wind electricity generation capacity in 2011). The state of Montana has a lower target of 15% electricity generation from renewables by 2015. Montana also offers a rebate covering 15% of the project installation cost, but does not offer any tax incentive for electricity generated from renewables. As a result, Montana (while ranked 3rd in the nation in wind energy potential [9]) has only managed to install 400 MW of electricity generation capacity from wind [4] (and is ranked 25th in the nation in wind electricity generation capacity in 2011).

As such, there is a pressing need for a national level RPS that can standardize and harmonize the various state-level RPSs by putting a floor on the minimum percentage of electricity to be generated from renewables by a target date applicable nationwide [138]. The individual states will still be free to set their own target (by taking into account their renewable resource potential and electricity demand) in consultation with the federal government (regarding the minimum percentage of electricity to be generated from renewables) which must not be lower than the federal target. This will allow potential investors in renewable electricity generation to have greater clarity at the national level about: (1) target date and minimum amount of electricity to be generated from renewables and (2) offered rebates and tax incentives.

6.2.7. Adopt a holistic approach to renewable energy policy implementation

The current U.S. renewable energy policies (based on tax incentives) are narrowly focused. Incentives (like tax credits) and penalties (like carbon tax) are important, but by themselves cannot single handedly overcome the obstacles to sustainable deployment of renewables. The various policy mechanisms recommended so far should not be seen as substitutes for each other that can work in isolation [139], but rather as complimentary policies that need to be implemented simultaneously (by all the concerned stakeholders) if the various barriers to the successful and sustainable deployment of renewables (for electricity generation) are to be overcome [121]. Therefore, there is a need for an all-inclusive integration of parties involved within the renewable energy supply chain (including research and development organizations, equipment manufacturers, commercial/residential renewable electricity producers, utilities, grid operators, policy makers, and regulatory bodies) in order to develop a comprehensive implementation approach (which also ensures that redundancy and duplication are avoided) to the sustainable deployment of renewables for electricity generation in the United States [128]. However, several trade-offs will still need to be made among the various policies. The trade-offs will consider but not be limited to the following areas: (1) implementation costs (2) short and long term expected benefits (i.e. increase in electricity generation from renewables and/or reduction in carbon emissions, etc.).

7. Conclusions and directions of future research

The paper analyzes the prospects, opportunities, challenges, technical state of the conversion technology, strategies, and policies for electricity generation from renewables in the United States. The article also gives guidelines on how to assess the effect of various sustainability indicators (like cost, environmental and social impact) to determine the optimal resource mix for generating electricity from renewable energy resources. Finally the paper recommends a number of rigorous policy instruments that can be used for optimizing future U.S. renewable energy policy. This will provide valuable information (including databases, insights, and recommendations) to energy policy makers (both at the federal and state level), investors in renewable generation projects, researchers (looking for future renewable resource usage and conversion technology trends), and all others with an interest in the sustainable development and deployment of renewable electricity generation projects across the United States.

To induce a sustainable shift towards renewable electricity (thereby allowing the U.S. government to set and meet renewable electricity targets), further research is recommended in the following high priority areas:

(i) **Reducing the cost of electricity generated from renewables**
To increase the share of electricity generated from renewable resources, it is essential that the financial viability of renewable technologies be demonstrated by ensuring that electricity generating cost continues to decrease. This can be largely achieved by increasing the conversion efficiency of renewable technologies. For example, the conversion efficiency of solar cells is defined as the percentage of the solar energy (to which the cell is exposed) that is converted into electrical energy. The efficiency of solar technologies has steadily improved in the past 30 years with current commercial solar cells offering up to 15% conversion efficiency [12]. Sustained investment in research and development is needed to translate efficiencies of 50% achieved in laboratory settings [13] to market-ready commercial solar cells.

(ii) **Developing an optimal smart grid**
To establish an optimal smart grid that can integrate electricity generated from different energy resources (including renewables and conventional) into the national power grid, further research and development needs to take place in the fields of: (1) electric grid infrastructure (from power production to transmission and consumption) that can accommodate addition of new technologies and/or to changes to existing ones; (2) weather forecasting models to anticipate supply of electricity from intermittent renewables; (3) remote sensors (with real-time information gathering and transmission capabilities) that can detect fluctuations (depending on the weather, time of day, and geographic location) in electricity demand and accurately assess the supply of electricity from renewable and conventional generators; (4) smart meters with the capability to allow differentiated peak/off-peak pricing (and net metering); (5) electricity storage technologies to mitigate against intermittency of some renewables (like solar and wind); (6) software models for simulation of grid operations across a range of electricity supply/demand and disruption scenarios; and (7) mathematical models that optimally balance the instantaneous electricity demand across the available supply from base-load generators (i.e. large-scale hydro and coal-fired power plants), various renewable resources, and on-demand generation from natural-gas power plants (to meet peak-time demand or compensate for drop in electricity supply from intermittent renewables).

(iii) **Designing robust renewable energy policies**
This paper recommends adopting a comprehensive approach to renewable energy policy implementation. In this regard the proposed policy initiatives need to move beyond the conceptual stage and their details (e.g. level of tax incentive and time horizon, level of subsidy for different renewables, level of carbon tax and/or emissions cap, level of FIT for different renewables, differentiated price level of renewable electricity under MGPO, minimum percentage of renewable electricity to be generated at the national level, etc.) need be elaborated.

In order to develop a robust set of renewable energy policies, policy makers will also need to take into account: (1) the various policy objectives (e.g. maximizing financial profit for renewable electricity producers, maximizing amount of electricity generated from renewables, minimizing GHG emissions, stimulation of depressed local economies in rural and/or under developed areas, etc.); (2) investor attitude (i.e. risk averse, risk seeking, or risk neutral) towards capital investments decisions by quantifying the risk in renewable electricity projects; and (3) the trade-offs (i.e. policy implementation costs, expected short and long term benefits to renewable electricity producers, utilities, consumers, and tax payers) among the various proposed policies.

It is also necessary to assess the efficacy, efficiency, equity, and feasibility of the proposed renewable energy policies. This will

require developing decision making tools that can determine the optimal allocation of individual renewable resources for electricity generation (in the United States) under different renewable energy policy objectives and incentives. This requires development of mathematical models that consider multiple criteria (including economic, environmental and social impacts) while determining the optimal renewable resource portfolio (at the national and state level) that can hedge against uncertainty in government policies, technological breakthroughs, and project investment risk.

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